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Catherine Letondal, Christophe Hurter, Rémi Lesbordes, Jean-Luc Vinot, Stéphane Conversy. Flights in my hands: coherence concerns in designing Strip'TIC, a tangible space for air traffic controllers. CHI 2013, SIGCHI Conference on Human Factors in Computing Systems, Apr 2013, Paris, France. pp 2175-2184, 10.1145/2470654.2481300. hal-00876550

HAL Id: hal-00876550

https://hal-enac.archives-ouvertes.fr/hal-00876550

Submitted on 29 Oct 2013

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Flights in my Hands: Coherence Concerns in Designing Strip'TIC, a Tangible Space for Air Traffic Controllers

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ABSTRACT
We reflect upon the design of a paper-based tangible interactive space to support air traffic control. We have observed, studied, prototyped and discussed with controllers a new mixed interaction system based on Anoto, video projection, and tracking. Starting from the understanding of the benefits of tangible paper strips, our goal is to study how mixed physical and virtual augmented data can support the controllers' mental work. The context of the activity led us to depart from models that are proposed in tangible interfaces research where coherence is based on how physical objects are representative of virtual objects. We propose a new account of coherence in a mixed interaction system that integrates externalization mechanisms. We found that physical objects play two roles: they act both as representation of mental objects and as tangible artifacts for interacting with augmented features. We observed that virtual objects represent physical ones, and not the reverse, and, being virtual representations of physical objects, should seamlessly converge with the cognitive role of the physical object. Finally, we show how coherence is achieved by providing a seamless interactive space.

Author Keywords: Tangible interaction; Augmented paper; Pen-based UIs; Distributed cognition; Participatory design; Ethnography; Air Traffic Control; Transport; Security.

ACM Classification Keywords: H.5.1. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms: Human Factors; Design; Measurement.

INTRODUCTION

Mixed interaction design has been studied through several approaches: tangible user interfaces (TUIs) [35, 11], augmented reality (in the sense of [26]), and all approaches that can be described as reality-based interaction [15]. Several models [35, 11], taxonomies [7], frameworks [12, 35, 15, 21] or guidelines [17, 34] have been published that inform the design of mixed interactions. They address its complexity, mainly through issues related to coherence of the mapping or coupling of physical and virtual elements [35].

However, recent literature points out the limits of TUIs. In TUI litterature (e.g [21]), coherence is achieved through mapping, i.e when the physical and the digital artefacts are "seen" as one common object. Mapping-based coherence thus involves how representative a physical object is of a virtual one. This has been challenged [6]. First, the claim that TUIs enable to physically manipulate abstract data has been questioned [20]. Second, addressing mixed interaction complexity cannot rely solely on a mapping-based coherence. In [26], Mackay warns about not spoiling the understanding that users have about the laws that dictate the behavior of physical objects by a behavior that is dictated by the humans who build the virtual system. In [13] Hornecker further questions the assumption that affordances of the physical world can be seamlessly transferred to computer-augmented situations: users actions are not always predictible, nor do their expectations about the behavior of the system, and it is not obvious for the designer to know which prior knowledge of the real world will be invoked.

We profited from the redesign of an Air Traffic Control (ATC) environment, an operational, complex system already based on basic mixed interaction, to gather new knowledge on mixed interaction design. The system (named Strip'TIC [14]) explores a solution that integrates interactive paper, handwritten notes and digital data, using digital pen and augmented reality technologies.

This paper presents the results of this investigation. Notably, we present how we addressed mixed interaction complexity through a view of coherence that departs from mainstream TUI models. In our context, physical objects and associated manipulations have an inner coherence due to their cognitive role as external representations [19], that designers must respect. A consequence is that physical objects represent mental objects rather than virtual ones. Furthermore, the virtual objects actually represent the physical ones, and not the reverse, which brings constraints on their design. Finally, we show how coherence is achieved by providing a seamless interactive space.

RELATED WORK

Our work relates to interface approaches that employ physical means of interaction or reality based interaction [15]. In this field, following the tradition of metaphor-based usability, a first research goal has been to find how to design interfaces that mimic the real world: the main idea was to build on prior knowledge to foster usability [15]. Research work following this goal includes reflection on how to give a physical form to digital objects [35], and also on mapping and coupling physical objects and their digital counterpart to enhance the coherence of the metaphorical relationship. An important issue has been to define tangible interfaces, either in terms of interaction models, e.g. [35], or through frameworks that describe the type and qualities of various dimensions, such as levels of mapping, metaphorical dimension [7] or concepts of containers, tokens and tools [11]. Characteristics of couplings are also described: in [7], the embodiment dimension describes the level of integration of input and output in tangible systems, while [21] classifies coupling according to the degree of coherence, as measured through several properties of links between virtual and physical objects.

A significant part of tangible interface research aims to explain not only prior knowledge or metaphorical scales, but also properties and affordances of the physical world these interfaces rely on [8, 12, 20]. In [12], Hornecker et al propose an analysis of physical interactions through four perspectives for the design of tangible interfaces: tangible manipulation, spatial interaction, embodied facilitation and expressive representation. Affordances of paper have been studied in depth by [32]. In [25], Mackay analyzes more specifically how paper strips support ATC activity. In [34], Terrenghi et al analyze tangible affordances through comparisons of different kinds of interactional experiences performed by similar physical and digital systems, such as comparing multiple items or creating spatial structures, with the aim of designing better digital systems.

Another field of research, instead of metaphorically extending digital systems to the real-world, aims at extending real-world objects by linking them to digital features through augmented reality [26]. This field notably includes augmented paper or paper computing research [33] which aims at integrating paper and digital documents.

Several views unify tangible interfaces and augmented reality, such as reality based interaction [15]. For designers, a more general issue thus becomes the allocation problem to either virtual vs physical objects. [17] for instance discusses how physical or virtual objects enable various tasks, such as disambiguating objects, supporting eyes-free control or avoiding mode errors. Some authors compare digital and physical according to efficiency in relation to specific tasks. In [28], McGee et al evaluate whether a paper-augmented system performs as efficiently as a digital system without losing the positive properties of paper, but rather focuses on the cost of recognition errors than on allocation issues.

Other approaches broaden TUIs definition. In [12], Hornecker et al rethink TUIs as interactive spaces, focusing on the quality of the corresponding user experience. In [6], tangibility is proposed as a resource for action instead as just an alternative data representation.

ATC ACTIVITY AND ITS INSTRUMENTATION

As said above, our study on mixed interaction is grounded on air traffic control (ATC). Air traffic controllers maintain a safe distance between aircraft and optimize traffic fluidity, usually working by pair. The planner controller predicts potential conflicts between aircraft. The tactical controller devises solutions to the conflicts, implements them by giving instructions to the pilots by radio, and monitors the traffic. Air traffic controllers currently use a combination of computer-based visualization (e.g. radar image) and tangible artifacts (paper strips) to manage traffic [25].

Specific control situation

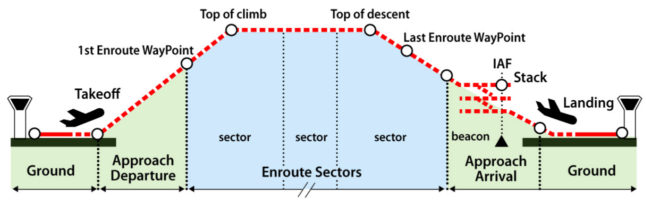

Figure 1: phases of flight and associated control areas. Final approach control manages aircraft from the stack and the IAF (Indicated Approach Fix) point before landing.

We have decided to ground our study on a specific ATC situation, the Approach Control (Figure 1). The traffic of Approach is complex and dynamic: aircraft are most likely ascending or descending; minimum separation in time and space between aircraft goes from 5Nm (8km), through 3Nm in the Approach area; to 2.5Nm just before landing to ensure 2 minutes between two consecutive planes. Therefore the time of analysis and action decreases rapidly as the aircraft get closer to the field.

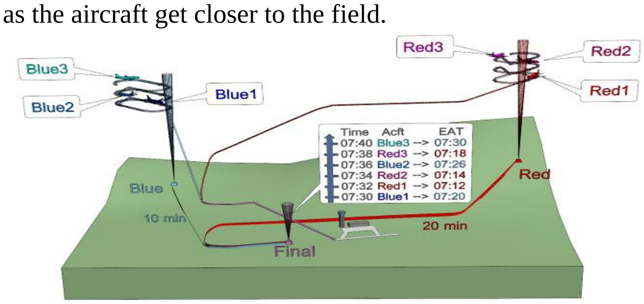

Figure 2: a stack and calculation of the Estimated Approach Time (EAT).

For traffic optimization purposes on a busy airfield, controllers try to get as close as possible to the maximum runway capacity i.e. the number of takeoffs or landings per hour (Figure 2). This is challenging since they need to optimize aircraft ordering and separation with a mix of takeoffs and landings. When the runway capacity is exceeded, controllers can delay the arrival of aircraft by piling them up into a ‘stack’ and making them perform horizontal loops. The first aircraft in the stack is assigned to the lowest altitude. Each new aircraft entering the stack is piled upon the previous one. The first aircraft that leaves the stack is the lowest one. When an aircraft leaves the stack, the controllers order each remaining aircraft in the stack to descend to the next lower altitude.

The management of the Arrival sector can even be split between two controllers: a controller for the management of incoming aircraft and the management of the stacks, and a controller guiding and sequencing aircraft from the stacks to the final axis of the runway. Splitting (or degroupment) is a critical phase since controllers have to reallocate a set of strips on an additional stripboard. Paper strips can either be physically passed between controllers or be duplicated. In this case, the last information handwritten on the strips must be reported orally to the supporting controllers.

Current instrumentation and tentative improvements

Controllers do not feed the system with the instructions they give to the pilot, neither through the computer-based part of the system, and of course nor through the paper-based part. This prevents the potential use of automation to help controllers regulate the traffic more efficiently and in a safer way. However, controllers do hand write the instructions on the strips to remember them. This has led the Airspace authorities in the EU and the USA to replace paper with digital devices (dubbed "electronic stripping" or stripless environment) in the hope that the instructions could be fed to the system. Although electronic stripping has been constantly improving during recent years, there is still reluctance to its being adopted. We suspect that such reluctance is partly due to the fact that screens do not offer the same level of interactivity as paper. In fact, the designers of electronic systems have devoted considerable effort to replicate interactions on the paper, be they prospective [29, 2], or operational (Frequentis SmartStrips or NAVCANStrips).

Considering the previous remarks, mixed interaction may be an appropriate approach to the improvement of the ATC environment. Caméléon early project [24] explored various technological alternatives to electronic stripping: transparent strip holders whose position could be tracked on a touch-screen, a pen-based tablet with no screen but with regular paper. However, these early prototypes were built with the technology of the mid-nineties and not all possibilities could be explored, especially those based on augmented paper.

Significance for research on mixed interaction

ATC has a number of properties that may shed a new light on mixed interaction. ATC is real: the realness of the activity can act as a magnifier of aspects about mixed interaction that would be overlooked with artificial activities. ATC is life-critical: even if accidents are rare (because the way the system works helps prevent problematic situations) some circumstances can lead to life and deaths situations. Controllers involved in the design of tools and procedures are constantly aware of their responsibilities, which make them cautious and concerned. ATC is time-constrained: since a flight cannot stop in the sky, orders must be given under constraints. This makes time-performance an important concern. ATC is heavily designed for performance: tools and procedures have been refined and tuned for years by their own users, which has led to a high level of safety and capacity. This stresses the usefulness and usability of new proposed features. ATC is demanding in terms of human cognitive capability, and qualification on a complex area can take years. Even subtle aspects of the instrumentation may have an impact on cognitive load and deteriorate performance. ATC controllers are extremely concerned by the instrumentation of their activity. They reflect on the tools and their procedures and are eager to improve them based on a deep internal knowledge. Even if all aspects are not new (e.g. Reactable [16] for real-time and reality), we were expecting that the combination of those properties would raise the level of implication, reality, deepness and details during the discussions.

PROTOTYPE DESCRIPTION

We have designed Strip'TIC, a novel system for ATC that mixes augmented paper and digital pens, vision-based tracking and augmented rear and front projection [14]. The paper strips, the strip board and the radar screen are all covered with Anoto Digital Pen patterns (DP-patterns). DP-patterns are small patterns (< 1mm width) used by the pen's infrared digital camera to compute the location of the pen on the paper.

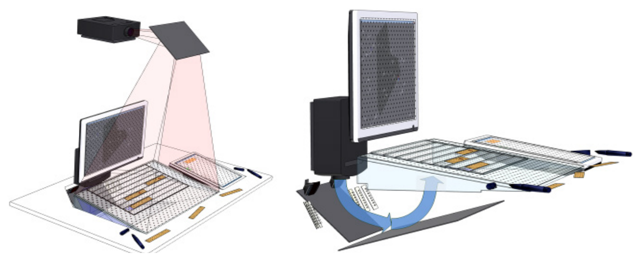

Figure 3: Strip'TIC. Top projector, radar screen, strip board, and side screen (left). Bottom projector casting images on a semi-opaque strip board, two mirrors, infrared LEDs, and webcams (right). Black dots depict pen-sensitive areas.

Users' actions with the digital pen are sent in real-time to IT systems wherever they write or point. Users can draw marks (e.g draw information on paper strips), write text (e.g. write aircraft headings), and point out objects (e.g. point out aircraft on the radar screen). The stripboard itself is semi-opaque: this enables bottom projection on the stripboard and strip tracking thanks to AR patterns printed on the back of the strips (Figure 4). Another projector displays graphics on top of the stripboard and on top of the strips. (Figure 3). Controllers can manipulate paper strips as they are used to with the regular system.

A cornerstone aspect of Strip'TIC is the mix between real and virtual strips. When a paper strip is put down onto the strip board, the tracking system recognizes it and projects a virtual strip under the paper strip with the bottom projector. Virtual strips are slightly larger than paper strips, which makes the paper strip borders 'glow' and acts as a feedback for the recognition of the strip. When lifting up a paper strip, controllers can use the digital pen to interact with its corresponding virtual strip. They can move it by performing a drag on its border, and also write on it. When setting the paper strip down onto the board, the virtual strip is aligned under it. The then-occluded handwritten notes of the virtual strip are projected on the paper strip (Figure 6).

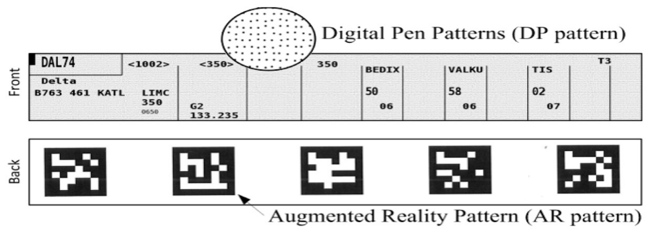

Figure 4: Front and rear of paper strip. Each strip corresponds to a flight, and displays information such as the level of entry, the route and a timed sequence of beacons the flight is supposed to overfly while crossing the sector.

We have implemented numerous features that rely on the combination of those devices: highlighting aircraft on radar when pointing on a real or virtual strip and vice-versa, projecting solid colored rectangles to colorize paper strips, adding real-time information on the strips (Figure 5), display of recognized hand-written texts, or even expanding paper strips with a virtual extension to address strip fixed size. Though technologically complex, the system is working in real-time and reactive. When introduced to Strip'TIC, controllers are usually eager to use it and discover all its features. The features that we specifically explored are discussed in the next sections.

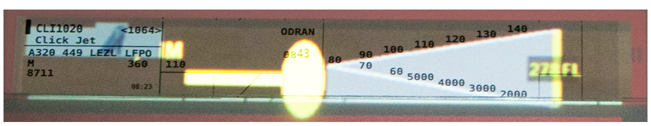

Figure 5: Paper strip with projected information. Highlighted beacon, distance aircraft-beacon, aircraft name, aircraft vertical profile and current position, current altitude.

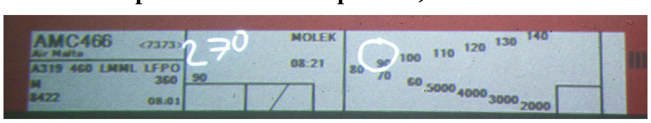

Figure 6: Paper strip with projected handwritten information.

METHODOLOGY

Our study was conducted as design-oriented research [5]. Hence the goal of our work was not to produce a 'final' prototype, but rather to gather new insights about mixed interaction through grounded discussions with users about the support of their activity by the prototype.

Designers: users and researchers

The observation sessions involved nine experienced controllers (more than 5 years experience) and six apprentices, and the design and walkthrough sessions involved nine other experienced controllers. All were French controllers involved in the three types of control (en route, approach and tower) from Bordeaux, Orly, Roissy and Toulouse. Our team is composed of 4 HCI designers and researchers (visualization, tangible and paper-based interaction, graphic design) and a controller.

Sessions with users

We conducted a series of iterative user studies, ranging from field observations and interviews, both transcribed and encoded, participatory design workshops involving video-prototyping, and design walkthrough sessions where the controllers tried the prototype by running scenarios such as ungrouping, conflict detection, stack management, etc. During these studies, we observed controllers and discussed with them to understand important aspects of their activity related to our design. We also experienced technical solutions with the Strip'TIC prototype, either to test it or to demo it and get immediate feedback. We let controllers play with it and react by proposing ideas, in order to get insights on how to co-evolve the activity with them toward a mixed system. In total, we completed 4 observation sessions in real context, 3 observation sessions of training controllers, 4 interview sessions, 5 brainstormings and prototyping sessions and 4 design walkthrough sessions. We also demoed our prototype to 21 French controllers, collecting 13 filled-in questionnaires, and to controllers from Germany, Norway and UK to get informal feedback.

Study conduct

Between the sessions with users, we implemented the ideas raised during the sessions. The fact that a feature would 'improve' the course of the activity was not the sole reason for further investigation. Instead, we were attentive to users' reactions and focus, especially when they were discussing the status of the artifacts, or if they considered them different based on some aspects (e.g. virtual or real). We were also attentive to users' discussions that may spark novel findings on mixed interaction and develop prototypes to investigate the raised issues further.

About 30 augmented features have been explored and prototyped during two years, using Wizard of Oz, paper, paper + video, Flash/Flex, or PowerPoint, and many have been implemented. In addition to the features described in Prototype section, we explored physical/virtual objects lifecycle management involving virtual but also physical strip creation (print/re-print), various interactions with physical strips (gestures, oral, pen-based) and application domain features such strip grouping, conflict or charge detection, various computation to support actions and decisions (distances, dates...), transitory state management, strip extensions, stripboard structure management (stacks, runways, simulation), temporal information (timelines, timers) (Figure 12), various informational features, macro commands, communication between controllers, and drawing or annotation on the screen.

DESIGNING MIXED INTERACTION IN ATC

We present in this section our reflections and observations gathered during the design of Strip'TIC. The first part clarifies basic allocation principles in the case of ATC, often already reported in the literature, that we review and supplement in the first part of this section. The second part addresses complexity and introduces coherence issues. It shows that they relate more to mixed physical/digital behavior than to mapping. The third part analyzes ATC temporal processes to introduce externalization as an important pattern to mitigate allocation problems and to design consistent tangible interactions.

Physical/virtual allocation principles

Positive properties

Paper strips exemplify several aspects of physical interaction, as described in [12]. Tactile properties make the strips graspable and enable lightweight interaction, such as slightly shifting a strip to trigger attention. Non-fragmented visibility of the stripboard and performative properties of gestures enable awareness among controllers. Spatial affordances support reconfiguration, and physical constraints with the stripboard format make some interactions easier or more difficult. In our study, observed affordances of physical strips are also in line with findings from [25], either regarding how manipulations of the strips helps build the picture of the current situation, or how the physical setting supports subtle cooperation and mutual awareness, for instance enabling non-intrusive cross-checking by working independently on different problems within the same collection of strips. Mackay also shows how bimanuality enables efficient handling of complex problems and why flexibility of paper [32] and handwriting may support rapid adjustment to evolving rules.

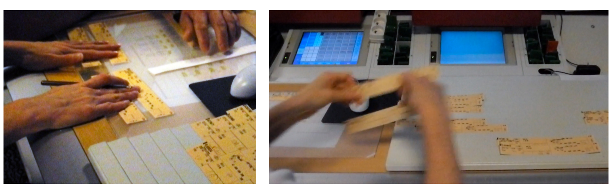

Figure 7: a) one stack in each hand; b) bi-stack bi-manual strip transfer from the planner board to the tactical one.

In our study, we focused on approach context, which involve many physical manipulations. We observed for instance how physical constraints were leveraged to help automate decisions or prevent undesirable actions [36, 18]: in a tower cab position (Blagnac), in case of potential wake turbulence after take-off (or landing), the controller encodes a delay condition for the next take-off by leaving the departing strip (of the aircraft causing the turbulence) *above* the next (ready to depart aircraft), in order to prevent any handwriting on it, and thus any take-off authorization. We also observed numerous bimanual interactions, for example during an approach instruction session where the planner held bundles of strips for each stack in each hand (Figure 7).

Negative properties

Tangibility also shows some limits [15] - that can sometimes be addressed by virtual features - such as strip fixed size, static stripboard structure, lack of space or manual operations. Lack of space is a recurrent concern when the traffic becomes dense, despite the fact that the stripboard is well organized, and although the small physical size of the control position enhances mutual awareness [25]. For instance, in a tower cab context, a controller piled strips so as to gain space, and another controller complained about badly designed paper forms that takes too much space: «*Paper, paper, ... a purely electronic form would be nice. In Blagnac, we currently have a paper sheet to fill in, with 60 lines for each minute... half of the sheet is useless. It takes room pointlessly.*». During design workshops, lack of space was addressed in different ways, for instance through the idea of extensible mini-strips. Controllers also complain about some physical manipulations. In particular, moving groups of strips is tiresome, as may happen when encoding evolving N-S or E-W flight streams on the board, as in the Bordeaux en-route center. In this center, the stripboard has grooves that let the strips be moved together, although in one direction only (to the top). We designed and discussed a bi-directional board with controllers in a workshop (Figure 8a), and their reaction was enthusiastic: « *This thing that goes up and down, yes, I can't wait to get this!* ». Concerning handwriting, one of them said: « *Let's talk about writing the time [on strips]. It takes time, it's heavy, it's a pain!* » This controller thus suggested to replace handwriting with speech recognition. Other problems with physical objects that we noticed and that we could address through augmentation include access to distant strips difficult to reach without disturbing or accidentally moving them, or slippage, that may happen with one-handed writing (Figure 8b) [23].

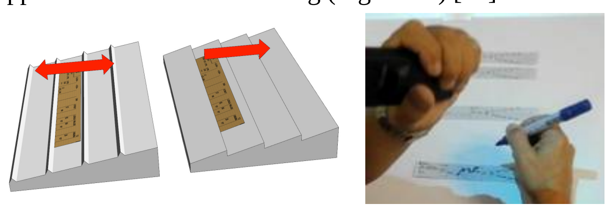

Figure 8: a) bi-directional grooved stripboard; b) one-handed writing when holding a microphone.

Managing mixed interaction complexity

We were concerned that augmentation, mixing physical and digital laws, brings complexity, and thus had to be carefully designed for the users to understand how it works [26, 13]. Regarding this matter, we observed a number of issues, but we also noticed interesting non-issues.

Issues

Some controllers were concerned about the "digital consequences" of their once easy to understand physical actions [3]: «*Does the system understand what I'm doing? How do I know? I'm writing something… what can happen in case it's not recognized?* […] *You have to be aware that by mixing electronic and physical systems, you will have a more complicated communication between each… this makes me anxious… it's going to be ultra-complex.*». Mixing physical interactions and virtual results may lead to discomfort. We walked with controllers through two prototypes (video and PowerPoint) of a tangible computation of an arrival sequence, which can be heavy in some settings having several stacks, such as in Orly (Figure 2): when a strip is laid on a special area of the board displaying expected final times, the system projects the corresponding stack exit time (Figure 12d). While the controllers found the idea useful and proposed several improvements in a quite participative way, one of them had some difficulties with this simulation area. While thinking aloud about the interface components he was looking at in the video prototype, he said: «*I have to forget this, for us … you need to get this out of my mind… [while hiding his eyes from this part of the board] …*». Unpredictable behavior may also result from some strips manipulations, such as strips askew (Figure 9a) or superposed: in the latter case, as illustrated by Figure 9, the system « works», i.e. virtual strips are projected, but more or less unrelated to the underlying strip. As advocated by [13] such issues have to be explored thoroughly and dealt with by the system, even if the manipulations, as the ones we mentioned, are unusual.

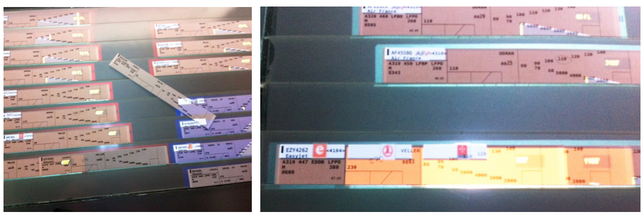

Figure 9: a) a strip askew; b) superposed strips.

Non-issues

By contrast, several concepts related to mixed interaction were quite easily accepted. Notably, all controllers played with the concept of virtual strips in several ways. They all appreciated the virtual strip as the visible counterpart of the physical strip laid onto the stripboard. To them, it is the main feedback that shows that the system understands what they are doing in physical space: « *It works, and this is the interesting point, that the system knows what we do.* » Feedback is probably one of the most important functions of augmentation (Figure 6, Figure 10). Beyond that, the main outcome is that this « understanding » from the system may bring support for detecting potential problems, such as warning about wrong written clearances or degroupment suggestions according to a growing number of strips detected on the board; warning from the system about possible missing actions, as played by a controller: « *Hey, you keep moving your strips but nothing has been written for a while, what's going on?* » These spontaneously proposed features show the importance of a « mutual understanding »: users need to understand the system, and to know that the system understands their actions.

As for the virtual strips and their physical counterparts, other facts struck us: controllers were quite comfortable with the isolated virtual strips – projected strips not corresponding to any « true » physical strip. We understood that these « informational » strips stand mainly for them as awareness during transient or temporary states (e.g sector degroupment): « *Indeed, having the virtual strip and the data on the real flight… it's just a matter of timing; if he [the controller of the adjacent sector] calls, that will save us some time!* », or for flights that controllers do not have to manage officially, such as flights transiently crossing the sector or very small tourist planes.

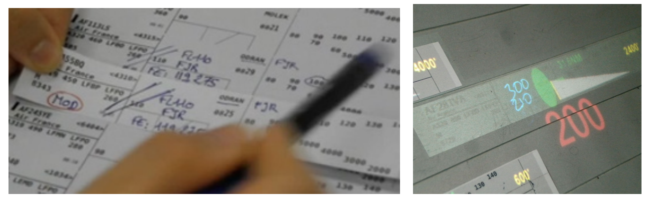

Figure 10: importance of feedback. a) MOD indicates that this strip is a modified and reprinted one; b) feedback for a handwritten heading.

Virtual strips were spontaneously proposed for incoming flights, too. To explain this acceptance, we had several explanations. One was that electronic strips are becoming more familiar in ATC culture. Another is that controllers clearly distinguish between « true » official strips that represent their individual responsibility and that belong to the whole ATC system with its flight plans, on one hand, and on the other hand, informational elements that belong to their own view of the traffic and to their own workspace. Another striking fact was that, under certain conditions, controllers did not bother having physical strip duplicates, either as re-printed strips for a given flight, or having a printed counterpart of a virtual strip. What could appear as complex, potentially leading to inconsistencies, in fact did not. This situation seemed in fact acceptable as long as the reprint of the strip is requested by the controller themself, or if the system informs about the status of a reprinted strip (Figure 10).

As for any systems, mixed systems need consistency. Users exploring the prototype during workshops insisted on how confident they are with the homogeneous space that is provided by the system, where all the interacting areas (screen, stripboard, paper) work the same way, with the Anoto pattern and digital pen: « *You have built a unique system for the radar screen and the strips, this goes toward harmonization, this is the way to go.* » Notably, the system enables users to interact with the strip even when it is removed from the board, which is not possible with an interactive surface. This is essential [34]: controllers often take one or more strips in their hands, and point onto the paper with the pen, while either staring at the screen or standing next to the control position, and discuss the current situation (Figure 11a). In this setting, tracking is no longer available, so that projection is understandably disrupted, but pen input and control still works (Figure 11b).

[26] warns about a digital system presenting either too much or too little information to the controllers, arguing also that the physical strips let controllers themselves adjust how much or how little of their mental representation is off-loaded into the strips through annotations and spatial manipulations. In an augmented setting, this physical adjustment is still possible, but we were aware that augmentation should not spoil this positive aspect, and that « just enough » digital information should be added onto the physical objects in order not to increase reading time and interpretation and their potential safety implications. Virtual objects of the prototype

do not have the same status in this regard: indeed, bottom projection can be occluded by paper strips, while top projection cannot. Interestingly, paper cannot occlude top projection either, which may lead to positive effects, when critical information, such as alarms, have to be visible, in as much that top projected objects are not opaque. By contrast, bottom projection is best suited for informative, less critical information that can be displayed in the strip extension.

Figure 11: a) Controllers holding paper strips and pen, and pointing onto it while discussing with other controllers standing in the control room; b) using Strip'TIC: the strip is still digitally interacting with other strips laid on the board.

Choosing between virtual or tangible interactions to support ATC temporal processes

This last part reports on more specific design issues related to the support of temporal processes. Current system developments in ATC such as [1] provide tools that use time-based information to manage trajectories. Maestro [2] already provides the controllers in Roissy with a tool to compute their arrival sequence according to explicit time slots. We explored whether augmentation could provide useful support to time-related features.

Structure of temporal processes in ATC

For air traffic controllers, safety means managing real-time events: planes arrive at their destination or take-off at given times. A critical part of the controller's task is to manage these events in real-time by talking to the pilots to give clearances. Another critical task is full preparation in order to ensure that these real-time actions will unfold properly and effectively. [22] describes ATC activity as a subtle combination of two modes of control: a proactive mode that consists – often for the planner – in building an efficient encoding of the problems so that they can be resolved very quickly and without errors, and a reactive mode which is often performed by the tactical through reactions to events (pilot calls, clearances, potential conflicts).

The two parallel modes occur at different timescales, as explained by a controller: «*the tactical […] is dealing with a problem at 15 nautical miles and we speak here about a conflict that will happen in 15 minutes*». Proactive mode is related to data encoding (flight integration, arrival sequence preparation), transition management tasks (sector degroupment, team replacement), and also problem encoding (filtering, searches, annotations, strip specific layouts). Reactive mode, characterized by fast context switches where data for problem solving must be at hand, is related to actions and decisions through physical gestures and tangible artifacts. ATC activity thus involves constant phasing between two timescales: that of the controllers, during which they organize their work, and real time, where real traffic occurs.

Temporal processes physical encoding

In [18], Kirsh describes how spatial arrangements support expert activities involving a preparation phase, and a high tempo execution phase. For instance, experts ensure that information needed to act quickly is available locally, and that actions can be performed almost automatically. To achieve this, they pre-structure their workspace physically to simplify choices, discard unrelated decisions, encode pre-conditions, and highlight the next action to take. For Kirsh, space also naturally encodes linear orders: items arranged in a sequence can be read off as the order they are to be used in. We observed similar orders in approach control with stacks and arrival sequences. In [10], Harper et al highlight how these arrangements encode an ordered set of tasks to perform: "ATCO work is not like an assembly line in which a recurrent sequence of steps has to be followed through, but one in which the work consists of putting the tasks to be done into a sequence of steps that can be followed through. […] This is how the ATCO is looking at the information presented in the strips, the radar and the R/T; to see what needs doing 'now', 'in a moment', 'sometime later on', and so on". These spatial orderings implicitly connect the two timescales we mentioned above: taken as traffic sequences, they correspond to the planes flying in real-time, but as tasks to perform, they also correspond to the control timescale. To be as precisely on time as possible, controllers also rely on their knowledge of action duration according to various contexts (including their own cognitive load): «*It's your internal clock, you know how long it takes you to perform standard actions.*»

Experimentation of time-based mixed tools

Based on this analysis, we explored how to turn these implicit relationships into a more explicit design of virtual temporal objects. We designed and implemented several prototypes, where time-related information was provided for various purposes, for instance to help calculate a stack exit time (Figure 12d). This was inspired by a kind of paper ruler that is used by Orly approach controllers as rough paper that helps visualize free time slots and calculate mentally (Figure 12c). We also implemented a tool to compute the time to reach a beacon (Figure 5) or to fly a given trajectory drawn as a polyline on the radar. In addition, we designed a timeline representing several flights heading to a common beacon [9] to analyze potential conflicts. Such tools are meant to add explicit time-related information to the already spatially structured linear orders. Time can also be visualized as dynamic, providing a sense of passing time through information that evolves visually, such as a timer to manage wake turbulence (Figure 12b), or progress bars (Figure 12a). We see these tools as complementary instruments to support phasing between the two timescales that we described above. What we observed however is that controllers quite efficiently rely on their own skills using physical and spatial tools both to adapt to real time and to schedule their actions.

In anticipation mode, approach controllers are in fact not so much interested in explicit time, but rather on ordering: «*You don't care about arrival time, what matters is that they [the planes]… are in a sufficiently spaced out and coherent order… not too close, not too far…* ».

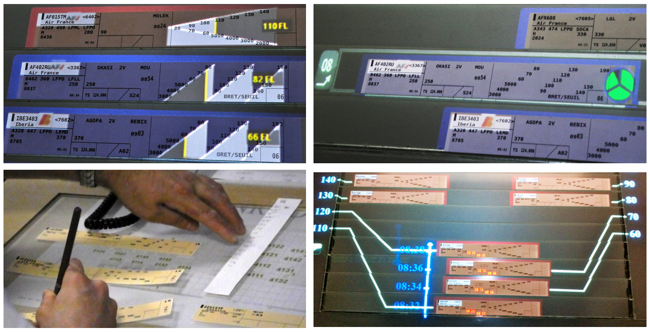

Figure 12: a) colors (light grey, yellow, dark grey) indicate past, present and future flight levels; b) wake turbulence take-off timer (green circle): the next departing plane has to wait for the AFR608 (indicated as heavy (H)) to move away; c) a rough paper ruler on the back of a strip to allocate an arrival sequence; d) tangible computation of an arrival sequence: allocation within projected time slots (blue), computed stack exit times (red), strips linked to their projected stack level (white - crossing links show a misordering).

One controller was in fact more interested in dynamic augmented features, as long as they are real-time, tactical control oriented, and help program timing or actions. While we were discussing an arrival timeline, he spontaneously proposed the idea of a countdown timer [4] to trigger action reminders: « *…10 ...9 …8 …0 …-1 …-2 … something to remind the tactical controller that it's time to act, to give an order to the pilot, and then even how much he is behind.* » This type of timer links control time and real-time by supporting the controllers in scheduling their actions.

DISCUSSION

In this study, we have chosen a tangible interaction perspective to analyze our observations, rather than an augmented paper one. As argued by [37], paper-based interfaces can be considered as TUIs, since they provide users with a physical modality of interaction and propose a close mapping between input and output. In addition, paper strip "thingification" makes them more relevant as physical cardboard handles, than as paper documents. Finally, a reason for adopting our perspective is that tangible interaction provides design models for coherence, that we wanted to investigate to address mixed interaction complexity. In this section, we first reflect upon our observations in terms of coherence, and more specifically in terms of representation. Then we describe how Strip'TIC addresses complexity through a seamless interactive space.

Challenging mapping and metaphorical coherence in TUIs

What do physical objects actually represent?

To date, as noticed by [20], one of the main stated concerns of tangible interfaces is how representative a physical object is of a virtual one. This explains why a mouse cannot be considered as a tangible interface: it does not represent any object of interest [35]. In [7], Fishkin describes tangible interfaces according to how closely physical input and virtual output are tied together (embodiment dimension) and how similar they are (metaphoric dimension). Unless used as tools, Holmquist [11] also describe physical objects as representing digital objects: a container potentially represents any virtual object, while a token stands for it. In these approaches, it seems that representation must be understood as both a statement of likeness and one of semiotics, where the physical object behaves as a *sign*, i.e something that stands for something else [35].

During the design of Strip'TIC, we were faced with this representation issue in a slightly different manner. What do physical strips actually *stand for* in this environment? For the controller, physical strips stand for flights crossing their sector and for their associated responsibility. They do not stand for virtual strips: the bottom projected strips mostly act as feedback, not as objects to manage. They do not stand for the flights displayed on the radar screen either: tracks on the screen and strips are different objects serving different purposes. The radar screen provides a view of real-time traffic, whereas the stripboard represents traffic and task achievement. Pointing onto a strip does in fact select the corresponding aircraft, but this just provides a visual transition between complementary views.

In the previous section, we have described spatial arrangements as an encoding for a set of control actions to perform, or for problems such as conflict detection. The physical layout and associated handwritten annotations of strips provide a structure that helps coordinate thoughts and build an image of the state of the system. What Kirsh in [18] describes as external representations enable memory to be offloaded (as stated for strips in [25]). In addition, they help to build persistent referents to internal information, that can be rearranged to perceive aspects that were hard to detect and to improve perception of semantically relevant relations [18].

Virtual objects representing physical objects

Virtual strips deserve a separate comment regarding their representational status. During phases where physical strips are missing on the control position, such as degroupment, it is the *virtual* strip that stands for the physical one, and the controller can interact with it as if it were the physical one. This status is important because it shows that virtual strips provide redundancy and thus robustness in cases of absent strips. The metaphorical expressivity of virtual strips also builds on prior cultural knowledge [15] that controllers have gained on electronic strips, as described in the previous section.

Toward a convergent design to support externalization through tangible interaction

Physical interactions supporting externalization and control

So, while physical strips do not seem to stand for any virtual object, they do stand for a responsibility for an aircraft and act as external representations of this responsibility. At the same time, Strip'TIC provides a true tangible space, i.e. a space where manipulations in physical space trigger events in the virtual space: moving strips on the board moves the associated projected data. Therefore, we can identify the two relationships described by the MCPrd model [35]: the physical strip *controls* digital data projection, but *stands for* an internal representation. On one hand, the physical strip acts as a tangible "window" to control the output projected onto the paper (Figure 13b). On the other hand, the physical strip acts as a cognitive handle to project and build [19] a mental picture (Figure 13c). Through physical manipulations, each of the two dimensions builds an image: a projected image, and an internal image of the current state of the situation. It should be noted that the projected image comes at no cost: controllers are not aware of this "window management" activity.

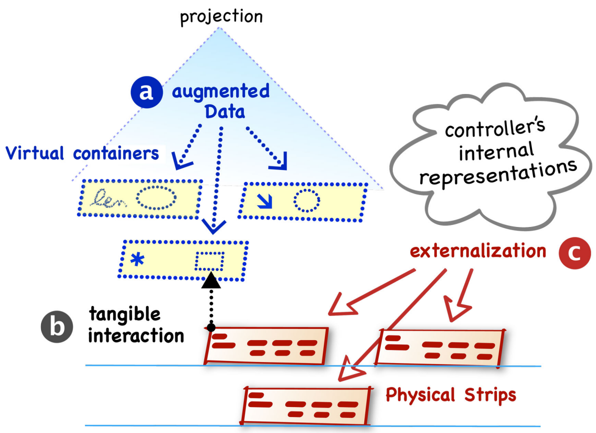

Figure 13: tangible strips (b) acting as *controls* and as *containers* for augmented data (a) and as *representations* and *tokens* for cognitive elements (c).

Implications for allocation of physical and virtual components

This analysis sheds light on our choices of allocation. As we described in the previous section, physical objects and associated manipulations have their inner coherence. So, as long as physical objects are able to provide the controller with external representations of their concerns, there is no need to overload them with additional explicit information. As described in the previous section, physical and spatial tools provide a sufficient encoding of objective time, orders and internal clock. By contrast, augmented data (Figure 13a) are needed to provide real-time perception and dynamic information on the current state of flights. Our analysis also helps to understand potential complexity issues, where the physical manipulations, such as tangible computation of stack exit times, did not exactly correspond to current practices, i.e., at least for some controllers, to externalizations on which they rely today.

A seamless and understandable interactive space

Complexity is also dealt with through the properties and the behavior of the components. Several of our observations highlight this aspect, both in terms of interaction devices and of human-system communication [3]. Controllers often commented on the homogeneous Anoto patterned environment, providing a uniquely addressable system. They also reacted particularly well to the system showing a « mutual understanding » through constant attention to user input (strip moves, handwriting recognition) and continuous feedback. Continuous feedback notably addresses issues discussed by [26] and [13], such as user understanding and expectations about the system behavior. The system shows additional kinds of continuity: 1) in the strip itself, which can be described as an *inherent mixed object*, combining a physical nature (paper) with a virtual content (printed information which can be re-printed on demand). This provides a mixity that might blur the frontiers between physical and virtual, as advocated in [31]. When data are projected onto the strip surface, a fine-tuning of luminosity may produce the effect of a composite rendering of printed and projected data. 2) merged displays: projected data cannot occlude printed information and vice versa, which adds to this seamless combination of tangible and virtual dimensions. Finally, coherence in Strip'TIC does not assume a constant coupling between physical and virtual components: disrupting strip tracking by removing a strip from the board does not prevent continuous use of the system, and most importantly, disrupting Anoto does not break the system either, since handwriting still works.

CONCLUSION

The Strip'TIC system provides us with the ability to explore mixed interaction in a context where physical interactions are effective and secure. Throughout our design reflections, we have seen that unlike usual TUI approaches, which rely on mapping and coupling of physical objects to virtual objects, coherence in Strip'TIC is based on other aspects. First, it relies on the mapping of *virtual to physical* objects that play a primary role as externalization of controllers internal concerns. Second, coherence consequently relies on a seamless connection of cognitive and tangible spaces that help the users to build a physical *and* virtual image of the situation. Third, the properties of the interactive space components and continuous feedback help users understand the mixed behavior of the system. Thus, compared to existing TUI models, our approach is complementary: we include the understanding and integration of artefact cognitive mechanisms as part of our design choices. Future work involves exploring issues about how augmented data may support externalization too, since this matter seems to be overlooked in current research. We also plan to investigate further about multitouch gestures combined with handwriting and pen-based interaction.

ACKNOWLEDGMENTS

We thank the air traffic controllers for their participation to the workshops, M. Cordeil for his help on coding and C. Savery and R. Moreau for the work on the video.

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